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Availability of Elemental Sulfur and Pyrite Concentrate—Market Economy Countries

A Minerals Availability Appraisal

By D. A. Buckingham

UNITED STATES DEPARTMENT OF THE INTERIOR

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UNITED STATES DEPARTMENT OF THE INTERIOR
Donald Paul Hodel, Secretary

BUREAU OF MINES
Robert C. Horton, Director

As the Nation's principal conservation agency, the Department of the Interior has responsibility for most of our nationally owned public lands and natural resources. This includes fostering the wisest use of our land and water resources, protecting our fish and wildlife, preserving the environment and cultural values of our national parks and historical places, and providing for the enjoyment of life through outdoor recreation. The Department assesses our energy and mineral resources and works to assure that their development is in the best interests of all our people. The Department also has a major responsibility for American Indian reservation communities and for people who live in island territories under U.S. administration.

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PREFACE

The Bureau of Mines is assessing the worldwide availability of selected minerals of economic significance, most of which are also critical minerals. The Bureau identifies, collects, compiles, and evaluates information on producing, developing, and explored deposits, and on mineral processing plants worldwide. Objectives are to classify both domestic and foreign resources, to identify by cost evaluation those demonstrated resources that are reserves, and to prepare analyses of mineral availability.

This report is one of a continuing series of reports that analyze the availability of minerals from domestic and foreign sources. Questions about, or comments on, these reports should be addressed to Chief, Division of Minerals Availability, Bureau of Mines, 2401 E St., NW., Washington, DC 20241.

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

°C	degree Celsius	Mmt/yr	million metric tons per year
km	kilometer	pct	percent
lb	pound	tr oz	troy ounce
mt	metric ton	US$/mt	U.S. dollar per metric ton
Mmt	million metric tons	yr	year

AVAILABILITY OF ELEMENTAL SULFUR AND PYRITE CONCENTRATE—MARKET ECONOMY COUNTRIES

A Minerals Availability Appraisal

By D. A. Buckingham[1]

ABSTRACT

Engineering and economic evaluations were performed by the Bureau of Mines on 14 Frasch sulfur, 1 native sulfur, and 21 metal sulfide operations in 11 market economy countries. The evaluation included discounted-cash-flow rate-of-return economic analyses at 15 pct to determine the average total cost of production of these two commodities and the potential availability of elemental sulfur (S) and pyrite concentrate.

The Bureau evaluated the potential availability of elemental sulfur and pyrite concentrate. Approximately 279 million metric tons (Mmt) of pyrite concentrate at 46 pct S is potentially recoverable from 422 Mmt of in situ metal sulfide ore. Nearly 89 pct of the total pyrite concentrate is available at an average total cost of production below the January 1984 pyrite concentrate market price ($43/mt). About 185 Mmt S is potentially recoverable from 253 Mmt of in situ elemental sulfur. About 99 pct of this sulfur is available at an average total cost of production below its January 1984 market price ($131/mt).

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INTRODUCTION

This Bureau of Mines report evaluates the availability of elemental sulfur and pyrite concentrate from market economy countries (MEC's). Some coproduct pyrite concentrate is evaluated here because it is recovered, for its sulfur content, along with other metal concentrates. Secondary sulfur, such as recovered elemental sulfur from the desulfurization of sour natural gas, petroleum, and tar sands, and byproduct sulfuric acid (H_2SO_4) from conversion of roaster and smelter off gases, is not included. Byproduct pyrite concentrates are not included since they are generally considered waste and are not recovered for their sulfur content. Recovery of secondary sulfur sources is nondiscretionary and cannot be adjusted to sulfur demand, since production from secondary sources is based on market requirements for low sulfur or sulfur-free products, or on removal of sulfur and its compounds for environmental reasons.

This report is part of a continuing series of reports in which the availability of selected mineral resources from domestic and foreign sources and factors affecting their availability are analyzed. The purpose of the analysis is to quantify engineering, economic, and resource parameters that would affect this availability.

Table 1 lists the 21 pyrite concentrate properties and 15 elemental sulfur properties included in this analysis. Jacobs Engineering Group, Inc., obtained information on 21 foreign properties under Bureau contract J0225020. Domestic deposit information was provided by personnel at the Bureau's Intermountain Field Operations Center, Denver, CO. Elemental sulfur and pyrite resources located in the Soviet Union, China, and other centrally planned economy countries (CPEC's)[2] were not analyzed in this study. Production cost estimates could not be supported because of the difficulty in collecting quantitative resource information.

This study consolidates past work and recent information from numerous sources as of January 1984. For each property demonstrated resources and commodity grades were defined, capital investments and operating costs for the appropriate mining and beneficiation methods were estimated, transportation costs to the nearest market were assessed, and an economic evaluation was performed. The analysis was performed in terms of January 1984 U.S. dollars. Individual property evalutions were aggregated into availability curves and tables to show potential elemental sulfur and pyrite concentrate availabilities at various average total costs of production.

Selection of properties is limited to known operations that have significant demonstrated resources of native sulfur or pyrite ore that can be mined using existing technology. The objective was to analyze the availability of at least 85 pct of known MEC resources from producing, past producing, developing, and explored deposits.

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[2] CPEC's: Centrally planned economy countries comprise the following: Albania, Bulgaria, China, Cuba, Czechoslovakia, the German Democratic Republic, Hungary, Kampuchea, the Republic of North Korea, Laos, Mongolia, Poland, Romania, the U.S.S.R., and Vietnam.

TABLE 1.—Evaluated properties, status, mining and benefication methods, and sulfur products recovered

Property	Production status[1]	Mining method	Beneficiation method	Sulfur product[2]	Map reference[3]
Cyprus:					
Kambia (Kampia)	P	Open pit	Flotation	Pyr	17
Mathiatis	P	..do	..do	Pyr	18
Sha (Shia)	P	..do	..do	Pyr	19
Iraq: Mishraq	P	Frasch	Filtration	S	14
Italy:					
Campiano	P	Room and pillar	Sizing	Pyr	20
Fenice Capanne	P	..do	Flotation	Pyr	22
Niccioleta	P	Sublevel stoping	Sizing	Pyr	21
Japan:					
Hanaoka	P	Horizontal cut and fill	Flotation	Pyr	33
Kosaka	P	..do	..do	Pyr	34
Shakanai	P	..do	..do	Pyr	35
Toyoha	P	..do	..do	Pyr	36
Yanahara	P	Sublevel stoping	Sizing	Pyr	32
Mexico:					
Coachapa	P	Frasch	None[4]	S	13
Jaltipan	P	..do	Filtration	S	11
Texistepec	P	..do	..do	S	12
Norway:					
Grong Gruber	P	Open stoping	Flotation	Pyr	31
Sulitjelma	P	Room and pillar	..do	Pyr	30
Portugal:					
Aljustrel	P	Horizontal cut and fill	Sizing	Pyr	26
Lousal	P	Opening stoping	..do	Pyr	27
Spain:					
Herrerias	P	Room and pillar	..do	Pyr	25
La Zarza-Calanas	P	Fill stoping	Sizing	Pyr	23
Tharsis	P	Open pit	..do	Pyr	24
Sweden:					
Kristineberg	P	Horizontal cut and fill	Flotation	Pyr	29
Langsele-Udden	P	..do	..do	Pyr	28
Turkey:					
Asikoy[5]	P	Open pit-underground	..do	Pyr	16
Keciborlu	P	Open pit-horizontal cut and fill.	Flotation and direct melting.	S	15
United States:					
Louisiana:					
Caillou Island[6]	P	Frasch	None[4]	S	7
Caminada	NP	..do	..do	S	8
Garden Island Bay	NP	..do	..do	S	10
Grand Isle	P	..do	..do	S	9
Texas:					
Boling Dome	P	..do	..do	S	5
Comanche Creek	NP	..do	..do	S	4
Culberson	P	..do	..do	S	2
Fort Stockton[7]	P	..do	..do	S	3
Long Point	NP	..do	..do	S	6
Phillips Ranch	NP	..do	Filtration	S	1

[1] P = Producer; NP = Nonproducer; D = Developing.
[2] Pyr = Pyrite concentate; S = elemental sulfur.
[3] Refers to location on figure 4.
[4] No beneficiation is performed.
[5] Property is scheduled to come on stream by mid-1985.
[6] Property was closed in May 1984.
[7] Property closed permanently owing to depleted resources in May 1985.

COMMODITY OVERVIEW

Sulfur differs from most major mineral commodities in that it is used as a processing and manufacturing reagent. Many agricultural and industrial products (phosphatic fertilizers, TiO_2 pigments) use intermediate sulfur chemicals in their manufacturing and processing. Elemental sulfur and other sulfur compounds must be converted to these intermediate chemicals (H_2SO_4 or CS_2) prior to use. After the use of these intermediate chemicals, most, if not all, of the sulfur content is discarded as a waste product and not incorporated into the final product. The consumption of sulfur in one form or another has been regarded as an index of a Nation's industrial development.

Sulfur occurs in a wide variety of forms, from native sulfur to sulfur compounds. Most elemental sulfur is obtained from native sulfur deposits and the desulfurization of sour natural gas, petroleum and tar sands. Sulfur also occurs in the form of pyrites, in ferrous and nonferrous metal sulfide deposits, from which pyrite and metal concentrates can be recovered. These concentrates are roasted to produce SO_2 which is converted to H_2SO_4 (*1*, p. 877-898).[3]

[3] Italic numbers in parentheses refer to items in the list of references at the end of this report.

PRODUCTION

Approximately 65 pct of the world's total sulfur production comes in the form of elemental sulfur from native sulfur deposits and the refining of sour natural gas, petroleum, and tar sands. The remaining sulfur production comes from pyrites, metallurgical operations, and other sources such as coal gasification and gypsum. Most of this sulfur is recovered as H_2SO_4. Figure 1 illustrates estimated world production distribution of all forms of sulfur by source for 1984 (*2*, pp. 831-849).

No single country is the dominant producer or supplier of sulfur and sulfur compounds. Approximately 50 pct of the world's total sulfur production comes from countries in which the industry is either partially or entirely government owned and/or operated. Table 2 lists total estimated 1984 world sulfur production by country and source. The CPEC's produce an estimated 35.6 pct of the world's sulfur; during 1984 the U.S.S.R. produced 9.3 Mmt; Poland, 5.4 Mmt; and China, 2.5 Mmt. The leading MEC producers in 1984 were the United States with 10.7 Mmt; Canada, 6.6 Mmt; Japan, 2.6 Mmt; and Mexico, 1.9 Mmt (*1*, pp. 877-898; *2*, pp. 831-849).

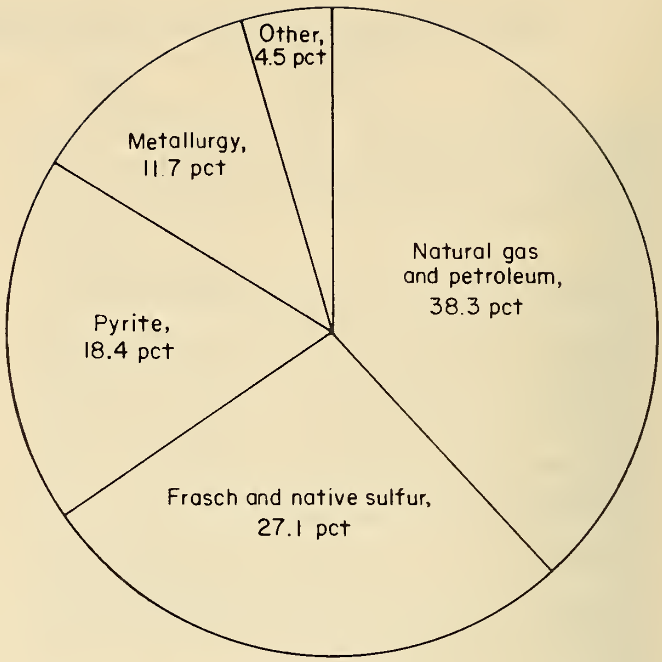

FIGURE 1.—Estimated distribution of world production of all forms of sulfur, by source, 1984.

TABLE 2.—Estimated 1984 world sulfur production in all forms, by country and source
(Thousand metric tons of 100 pct S equivalence)

Country	Natural gas and petroleum	Frasch and native sulfur	Pyrite	Metallurgy	Other	Total	Share of total, pct
MEC's:							
Canada	5,727	0	7	875	0	6,609	12.8
Japan	1,140	0	260	1,172	0	2,572	5.0
Mexico	461	1,364	0	100	0	1,925	3.7
Portugal	0	0	105	0	5	110	.2
Spain	7	0	1,100	120	3	1,230	2.4
United States	5,214	4,193	W	962	283	10,652	20.5
Other MEC's	4,661	710	2,004	1,716	1,041	10,132	19.5
CPEC's:							
China	0	200	2,100	0	350	2,650	5.1
Poland	30	5,000	0	300	20	5,350	10.3
U.S.S.R.	2,600	2,600	3,300	800	40	9,340	18.0
Other CPEC's	8	5	682	30	589	1,314	2.5
Total	19,848	14,072	9,558	6,075	2,331	51,884	100

Source: Morse (*2*).

CONSUMPTION

Sulfur is consumed in a wide variety of forms; the most common are elemental sulfur and H_2SO_4. Figure 2 details the sulfur-H_2SO_4 supply and end-use relationship. These two materials find a wide variety of uses including agricultural products, nonferrous metal and iron and steel processing, plastic and synthetic products, paper and pulp manufacturing, and pigment production. In 1983, total world consumption of all forms of sulfur was about 53.5 Mmt: Production of H_2SO_4 accounts for nearly 85 pct of the consumption of all forms of sulfur. Fertilizer manufacture consumes 55 pct of all forms of sulfur, mostly as elemental sulfur that is converted to H_2SO_4. The United States and the U.S.S.R. are the world's leading consumers of all forms of sulfur, each consuming about 11 Mmt/yr (*3*, p. 783).

COMMODITY PRICES

After 1965, the historically stable elemental sulfur market experienced a period of short supply in MEC's, with the deficit being made up by heavy withdrawals from producers' stocks in the United States. This, coupled with a rapid growth in the fertilizer industry, resulted in abnormally high prices in 1967 and most of 1968. In late 1968, a serious oversupply developed, the effects of which were magnified by a retrenchment in the fertilizer sector, the entrance of low-priced imports, and a weakening of export prices. The subsequent general collapse of the sulfur market continued through most of 1973. Prices began to rise again in 1974, decreased in 1977, then after a slight increase in 1978, became quite volatile, resulting in record high prices by 1981.

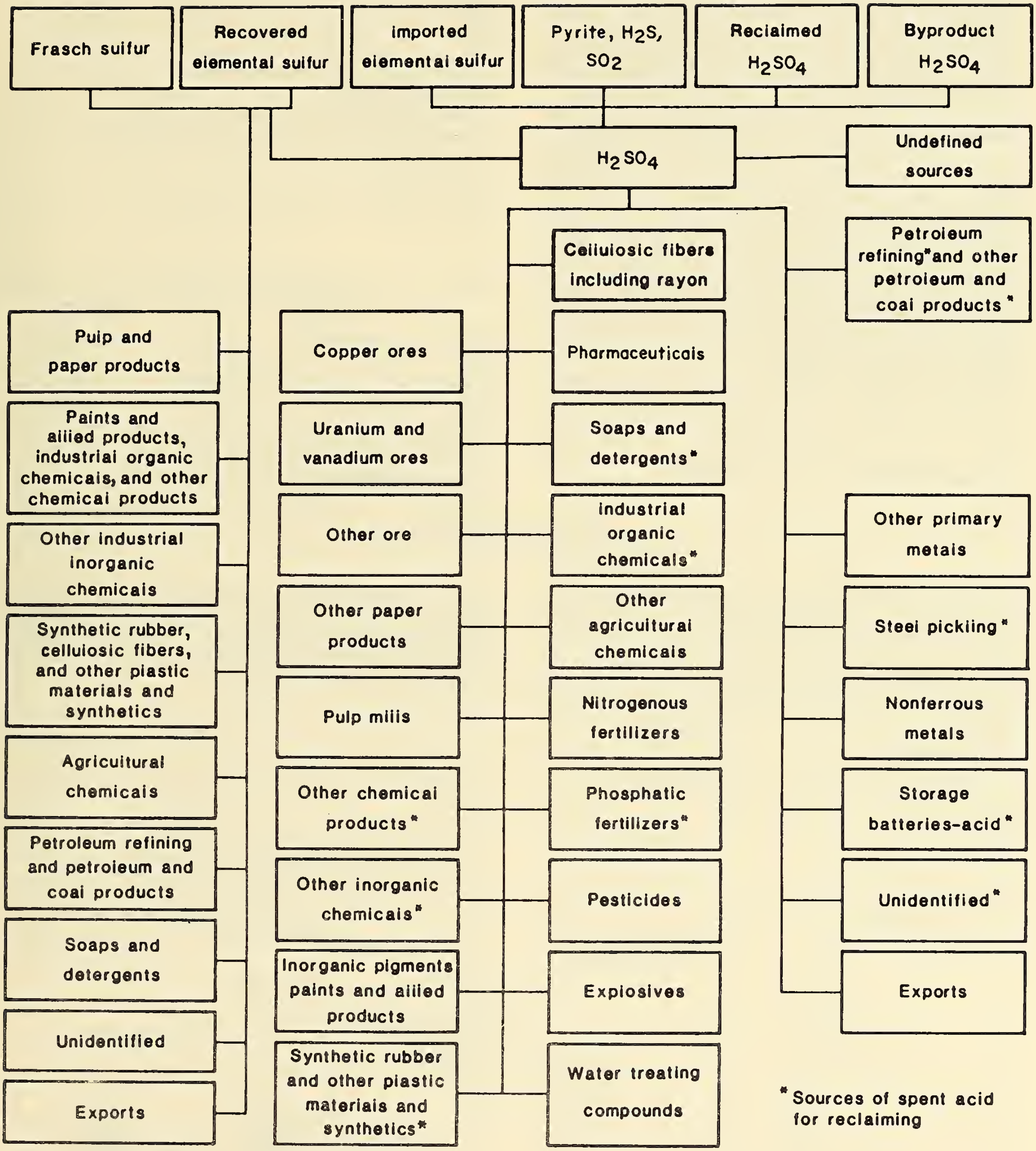

FIGURE 2.—Sulfur-H_2SO_4 supply and end-use relationship.

The reasons for these price increases were relatively complex and include (1) a rapid increase in demand by fertilizer manufacturers, both domestically and worldwide; (2) the high profitability of the fertilizer sector, which allowed high sulfur prices to be passed on to consumers; (3) the recognition that sulfur production costs, especially those of Frasch sulfur, has increased substantially; and (4) logistical problems that restricted deliveries. The economic recession that began in late 1981 caused a decrease in sulfur demand both domestically and worldwide through 1982 and into 1983.

In 1982 and 1983, Saudi Arabia brought large volumes of recovered elemental sulfur to the world market, and Iraq, despite the ongoing war with neighboring Iran, was able to return to the world marketplace. Because of this, sulfur prices softened in 1982 and fell further in 1983 (*3*, p. 790; *2*, pp. 831-849). In 1984, elemental sulfur prices began to rise, reaching their highest level since 1981, partially because of decreased production from Saudi Arabia, owing to damage to their Jubial sulfur-prilling facilities, and to decreased oil production. Table 3 lists the average reported price for elemental sulfur over the last 5 yr.

Prices for a pyrite concentrate containing 45 to 51 pct S have remained stable over the past 10 yr owing to low demand. However, with the recent increase in demand and rising price for elemental sulfur, more interest has been given to pyrite production. Table 4 lists the pyrite concentrate and other commodity prices used in the economic analysis.

TABLE 3.—Elemental sulfur market prices,[1] f.o.b. mine or plant

Year	*Price,[2] US$/mt*
1980	$97.36
1981	121.11
1982	120.74
1983	100.76
1984[3]	130.90

[1] Listed prices are U.S. market prices, f.o.b. plant or Gulf port, Louisiana and Texas.
[2] Actual year dollars.
[3] Elemental sulfur market price used in this analysis.

Sources: Morse (*2*, p. 834); Engineering and Mining Journal (*4*, p. 27).

TABLE 4.—Pyrite concentrate and commodity market prices[1]

Commodity		*Price, January 1984 US$*
Pyrite concentrate, 51 pct S[2]	per mt	$42.99
Copper	per lb	.71
Gold	per tr oz	370.89
Lead	per lb	.25
Silver	per tr oz	8.18
Zinc	per lb	.49

[1] Based on U.S. market prices.
[2] Market price of a pyrite concentrate used in this analysis.

Source: Engineering and Mining Journal (*4*, p. 27).

METHODOLOGY

The Bureau of Mines (*5*) has developed a methodology for the analysis of long-run mineral resource availability. An integral part of this system is the supply analysis model (SAM) (*6*), developed by personnel of the Bureau's Minerals Availability Field Office. This interactive computer system is an effective mathematical tool for analyzing the effects of various parameters upon the economic availability of domestic and foreign resources. The flow of the Bureau's Minerals Availability program (MAP) evaluation procedure from deposit identification to development of availability information is illustrated in figure 3.

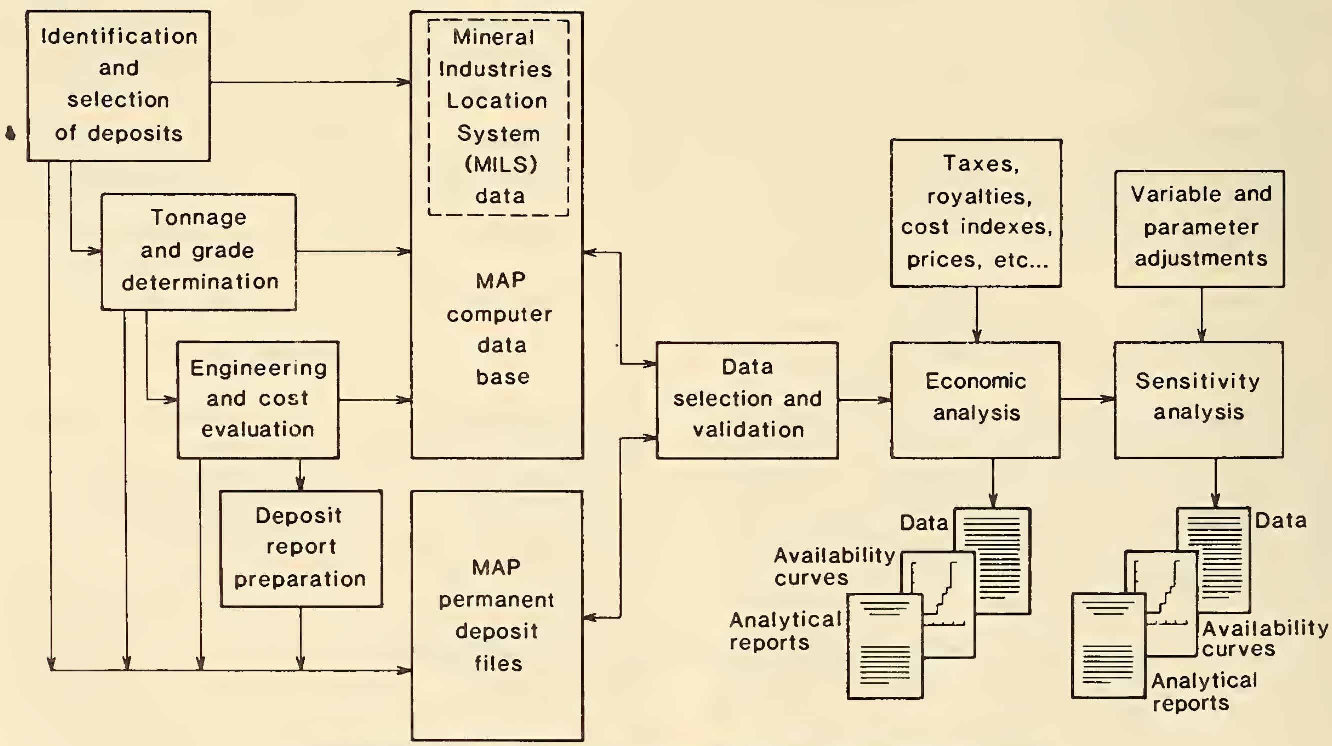

FIGURE 3.—Minerals Availability program deposit evaluation procedure.

Resurce grade and tonnage data included in this report are derived from contractor-supplied company data, published and unpublished sources, and Bureau and U.S. Geological Survey sources and estimates. Tonnage quantities and grade as of January 1984 are evaluated based on these data in relation to physical and technological conditions that exist at each deposit. Certain assumptions are inherent in this evaluation. First, all operations are assumed to produce at full design capacity throughout the productive life of the deposit, except when the actual production capacity is known. Second, operations are assumed to be able to sell all of their elemental sulfur or pyrite concentrate output at the determined average total cost of production and obtain at least the minimum specified discounted-cash-flow rate of return (DCFROR) of 15 pct.

COST ESTIMATION

Capital investments and operating costs for appropriate mining and processing methods are evaluated for each operation. Actual costs are used where available. However, if actual data are lacking, costs are developed based on data from similar existing operations or from the Bureau's cost estimating system (CES) manual (*7*). Where appropriate, capital and operating costs have been updated to January 1984 U.S. dollars according to local currency exchange rates and individual country inflation indices, weighted proportionately by the percentage share of labor, energy, equipment, and materials and supplies within each category on a countrywide basis.

Capital expenditures are determined for acquisition, exploration, and development; purchase and construction of mine and mill equipment and facilities; infrastructure; and working capital. Infrastructure includes capital costs for development of the operation that cannot be allocated to specific elements (mine, mill, smelter), such as access roads, utilities, personnel accommodations, and port facilities. The working capital is a revolving cash fund calculated on the basis of 60 days of operating expenses. Environmental costs for items such as water treatment and land reclamation are included if known. Initial capital costs are depreciated from the actual investment year to January 1984. The undepreciated portion is treated as a capital investment in January 1984. Reinvestments varied according to capacity, production life, and age of facilities. Total operating costs include labor, materials, overhead, utilities, and research. Transportation costs to market facilities (port terminal, sulfuric acid plant, or smelter) are also determined for each operation.

ECONOMIC ANALYSIS

Data are entered into the Bureau's SAM system, once all costs and engineering parameters are estimated. Economic analyses are performed on each operation, using DCFROR techniques to estimate the constant-dollar long-run price at which elemental sulfur and pyrite concentrate would need to be sold so that revenues are sufficient to cover all costs of production, including a prespecified rate of return on investment. For this analysis, a 15-pct DCFROR was considered necessary to cover the cost of capital plus risk. The DCFROR is most commonly defined as the rate of return that makes the present worth of cash flow from investments equal to the present worth of all after-tax investments (*8*).

The SAM system contains a separate tax-records file for each nation and State. Relevant taxes under which a mining firm would operate include corporate income taxes, property taxes, and any royalties, severance taxes, or other taxes that pertain to mining and processing of elemental sulfur and pyrite concentrate. These taxes are applied to each property with the assumption that each operation represents a separate corporate entity.

AVAILABILITY CURVES

Upon completion of the DCFROR analysis, all evaluated properties are simultaneously analyzed and aggregated into a total availability curve. This availability curve is the total amount of elemental sulfur and/or pyrite concentrate potentially available from the evaluated operations. Two total availability curves were generated: one for the elemental sulfur properties and one for the pyrite concentrate properties.

Elemental sulfur and pyrite concentrate availability are presented in these curves as a function of the average total cost of production associated with each operation, ordered from properties having the lowest average total cost of production to those having the highest. The potential availability of each commodity is determined by comparing these values with a long-run constant-dollar market price. The total recoverable tonnage potentially available at or below this price-cost value is read directly from the availability curves.

Annual availability curves can also be constructed. These curves represent the total availability of elemental sulfur and/or pyrite concentrate in any given year, based on the development and production schedules proposed for each operation.

GEOLOGY

Sulfur is widely distributed in nature. It is found in a wide variety of rocks and environments in its elemental form, as combined sulfide and sulfate minerals, and as organic compounds in fossil fuels. It is the 13th most abundant element and constitutes 0.6 pct of the earth's crust. Sulfur-containing deposits can be divided into six types: elemental or native, petroleum and tar sands, sour natural gas, coal and oil shale, metal sulfide (pyrite), and sulfate (gypsum) deposits. Elemental or native sulfur deposits, metal sulfide (pyrite) deposits, and sour natural gas are the most important and supply most of the world's sulfur. Only native sulfur and pyrite deposits are discussed in the following sections, since they are the only deposit types covered in this report. Figure 4 shows the location of the elemental sulfur and pyrite concentrate operations (*1*, pp. 882-883: *9*, pp. 607, 613-617).

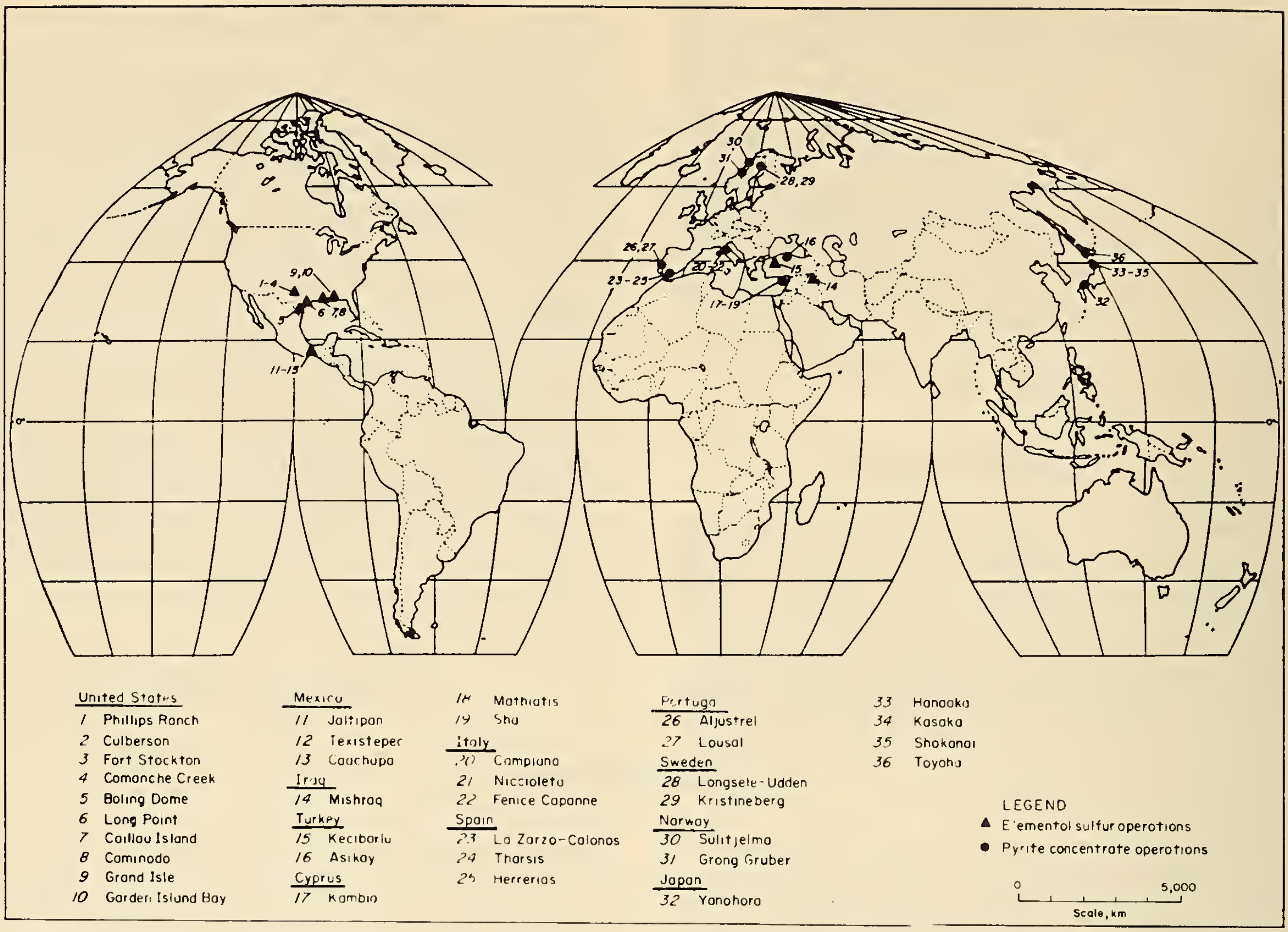

FIGURE 4.—Location of elemental sulfur and pyrite concentrate operations.

NATIVE SULFUR DEPOSITS

Elemental sulfur deposits are associated with anhydrite caprock overlying salt diapirs and bedded anhydrite evaporite formations. Bacterial attack on anhydrite produces lenses of limestone impregnated with elemental sulfur (*9*). Examples of these types of salt diapir deposits occur on the gulf coasts of Louisiana and Texas in the United States, and of Vera Cruz, Mexico (*10*). Bedded evaporite deposits of exploitable native sulfur occur both in west Texas, and in the Mogul region of northern Iraq. The west Texas deposits are associated with lenses or chimneys of anhydrite collapse breccia. The Iraqi deposit is associated with a dome-shaped anticline structure (*11-12*). The only native sulfur deposit of volcanic origin evaluated in this report is the Keciborlu sulfur operation in western Turkey. Sulfur mineralization occurs in a soft, highly altered, and decomposed rhyolite dike as veinlets and irregular nodules, and was formed as a sublimate from sulfur-rich volcanic gases (*13*).

PYRITE DEPOSITS

Ferrous and nonferrous metal sulfide deposits are also sources of sulfur. Ferrous metal sulfide deposits are the most important; they are generally massive high-grade ore bodies containing pyrite averaging about 40 pct S. These deposits are primarily exploited for their sulfur content in the form of pyrite concentrates, which can be converted to H_2SO_4. These deposits may also contain small amounts of copper, lead, zinc, gold, and silver that can be recovered as byproducts. Such deposits occur widely throughout the world.

Examples are found in the Iberian Pyrite Belt of southern Portugal and southwestern Spain. Stratiform polymetallic pyritic ore bodies occur within a suite of felsic and mafic volcanic rocks and siliceous sediments. Three types of sulfide mineralization are recognized. The first two types are massive and disseminated pyritic ores ranging from less than 35 to 51 pct S; both are syngenetic-sedimentary in origin. The third type is epigenetic stockwork pyritic ore of about 5 to 25 pct S (*14*, p. 63, 65; *15*, p. 32).

The ferrous metal sulfide deposits of Cyprus occur as both massive and disseminated pyritic ore bodies associated with pillow lavas, which fringe the Troodos Massif. Ore bodies that occur as disseminations in the pillow lava average about 20 pct S. Massive ore bodies, where replacement of the pillow lava is more complete, range from 40 to 48 pct S. Shapes and sizes of individual ore bodies vary from irregular to near horizontal-lenticular and range from 200 m wide and 600 m long to 15 m wide and 100 m long (*16*, pp. 38-39).

Italy's three pyrite operations are associated with hydrothermal deposition along faulted contacts between phyllitic schists and cavernous limestones of the Tuscany series. Both massive and disseminated vein pyrite ore

bodies are present. The sulfur grade of the pyrite for the three operations ranges from about 8 to 41 pct S.

Another system of sulfide ore bodies is the Kuroko type deposits of the Akita Prefecture in northeastern Japan. These ore bodies are stratabound polymetallic sulfide-sulfate deposits that occur in acidic volcanic rocks. The deposits are closely related to submarine volcanic eruptions of dacite or rhyolite rock types and are important sources of copper, lead, zinc, gold, and silver; but they are considered here because of the large amount of pyrite contained in the ore. Four ore zones have been recognized: a barite-spharlerite-galena zone (Kuroko ore) consisting mostly of chalcopyrite, pyrite and tetrahedrite; a barite, pyrite, and chalcopyrite zone (Han-Kuroko ore); a zone of almost all pyrite and chalcopyrite (Ohko ore); and a zone of pyrite, chalcopyrite, and quartz (Keikoh ore). Kuroko type deposits can show very irregular shapes and variable sizes. Average pyrite-sulfure grade can range from 19 pct (Keikoh ore) to 47 pct (Ohko ore). Kuroko deposits are consideed to be of submarine hydrothermal sedimentary origin (*17*, p. 171; *18*, p. 137).

The Yanahara Mine in southwestern Japan in the Okayama Prefecture is a massive ore body of almost pure pyrite with some intrusions of rhyolite. Pyrrhotite and magnetite are found near the margins. The average sulfur grade of the pyrite is 46 pct.

The two Norwegian pyrite deposits are related to the Koli Nappe sequences of the central Norwegian Caledonides. The Joma deposit of the Grong Gruber operation is imbedded in a sequence of basaltic greenstones. This deposit consists of (1) a massive pyritic layer interbedded with meta-limestone and chlorite schist lenses, and (2) layers of massive chalcopyrite-pyrrhotite. The average grade of the pyrite is 32 pct S for this deposit. The Sulitjelma deposits lie at the base of the Sulitjelma Amphibolites and contain massive pyrite, disseminated pyrite, and chalcopyrite-pyrrhotite ore averaging approximately 14 pct S (*19*, p. 745; *20*, p. 311).

Sweden's principal pyrite mines, the Kristineberg, and Langsele-Udden operations, are located in northeast Sweden in the south-central part of the Skellefte field. These ore bodies occur in the contact zone between a volcanic and a phyllite series. A few occur several meters below the contact. Ore bodies range in size from a few hundred metric tons to several million metric tons. They are generally elongated lenses and slab-shaped bodies of massive pyrite with varying amounts of chalcopyrite, sphalerite, galena, pyrrhotite, and arsenopyrite. Minor amounts of antimony and bismuth as well as gold and silver may also occur. Sulfur content of the pyrite ore ranges from about 12 to 36 pct (*21*).

The Asikoy Mine is located in northern Turkey. The associated ore body occurs in a lens of mafic volcanic rock isolated within a younger graywacke-argillite sedimentary sequence. Pyrite is dominant with variable amounts of chalcopyrite and some bornite concentrated in the upper part of the ore body. Two types of ore exist and are somewhat gradational. The disseminated sulfide ore is principally pyrite (35 pct S) disseminated in a pillow lava breccia. The massive sulfide ore also consists of pyrite (42 pct S) with some copper sulfide mineralizations.

SULFUR RESOURCES

Resources in this report are categorized according to the mineral resource-reserve classification system developed jointly by the U.S. Bureau of Mines and the U.S. Geological Survey (USGS) (*22*). (See figure 5.) Table 5 lists estimated world sulfur resources by type and level. World sulfur resources are considerable. Estimates vary widely owing to the different deposit types and the lack of data for many of these deposits.

The Bureau has established a reserve base for sulfur. This reserve base includes demonstrated resources (measured plus indicated) that are currently economic, or marginally economic (marginal reserves) and some that are subeconomic (subeconomic resources). Figure 6 compares Bureau and USGS resource estimates with the resource estimates analyzed in this report. The demonstrated resource evaluated in this report total approximately 675 Mmt (253 Mmt S and 422 Mmt pyrite ore). This tonnage comprises about 2 pct of the USGS total of 32 billion mt and about 25 pct of the Bureau's reserve base estimate of 2.7 billion mt (*3*, p. 785).

Table 6 compares the demonstrated resources of this report with the Bureau's reserve base estimates. Direct comparison of the demonstrated resources of this report with the Bureau's reserve base is difficult owing to the lack of a breakdown of the reserve base by deposit type.

TABLE 5.—Estimated world sulfur resources, by deposit type
(Million metric tons)

Deposit type	Demonstrated[1]	Identified[2]	Hypothetical and speculative
Natural gas and petroleum:[3]			
United States	NA	285	1,204
Remaining world[4]	NA	1,037	2,107
Elemental sulfur:			
United States	67	234	254
Remaining world[5]	186	386	203
Metal sulfides:			
Pyrites:			
United States	NA	102	20
Remaining world	294	534	534
Base metals:			
United States	NA	102	305
Remaining world	128	290	168
Other:[6]			
United States	NA	29,059	104,044
Remaining world	NA	NA	NA
Total	675	32,029	108,749

NA Not available.
[1] Data from the 36 MEC properties evaluated in this report.
[2] Includes demonstrated.
[3] Includes tar sands.
[4] Includes native sulfur in volcanic deposits.
[5] Includes other MEC's and CPEC's for the identified, hypothetical, and speculative resources.
[6] Estimate is large; includes organic sulfur compounds and pyrite in coal and oil shale, and sulfate (gypsum) desposits.

Source: Bedenlos (*9*, pp. 613-617).

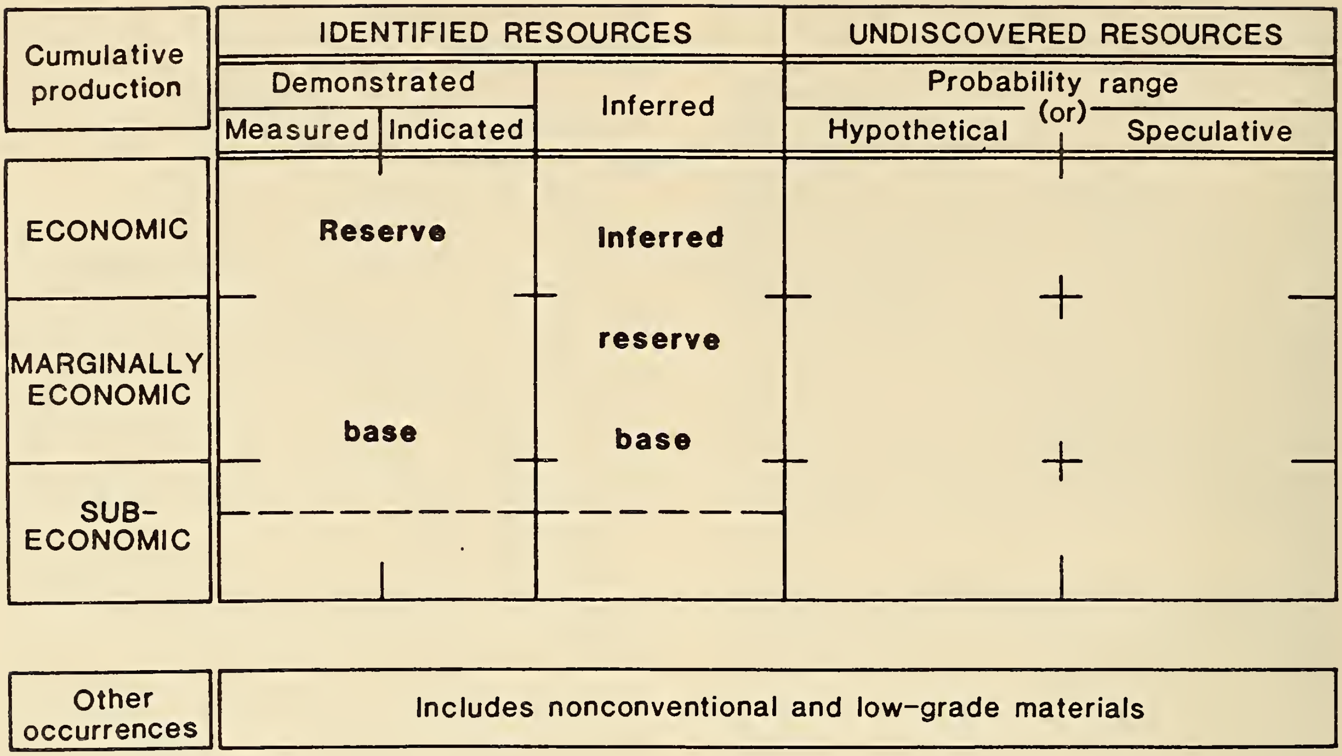

FIGURE 5.—Mineral resource classification categories (22).

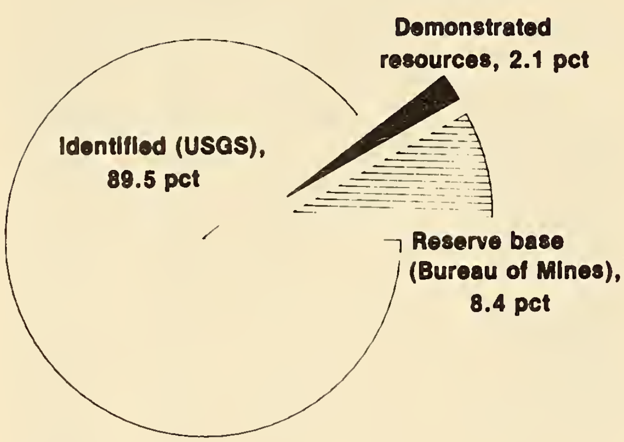

FIGURE 6.—Comparison of world sulfur resources estimates (total 32,029 Mmt).

TABLE 6.—Estimated resources of elemental sulfur and pyrite concentrate

(Million metric tons)

Country[1]	Demonstrated resources[2]			Reserve base[5]
	In situ	Recoverable[3]	Recovered[4]	
ELEMENTAL SULFUR				
Iraq	135.1	W	W	200
Mexico	50.1	37.5	37.2	100
Turkey	1.4	W	W	NA
United States	66.5	66.5	66.4	175
Total	253.1	200.0	184.5	475
PYRITE CONCENTRATE				
Cyprus	W	W	W	NA
Italy	36.9	35.4	29.1	15
Japan	75.6	78.2	29.7	10
Norway	25.4	26.8	11.0	NA
Portugal	139.3	97.4	97.4	NA
Spain	115.1	98.4	98.4	30
Sweden	W	W	W	NA
Turkey	W	W	W	NA
Total	421.6	363.4	278.9	55

NA Not available.
W Withheld to avoid disclosing company proprietary data; included in total.
[1] Data from other countries are not available.
[2] Estimated as of January 1984, as analyzed in this report.
[3] Pyrite concentrate estimate includes mine dilution; Japan and Norway have the highest dilution, averaging 20 and 39 pct, respectively.
[4] Some loss may occur during processing.
[5] Bureau of Mines estimate; total world reserve base for combined sulfur in all forms is estimated at about 2.7 billion mt (*3*, p. 785).

EXTRACTION AND PROCESSING TECHNOLOGY

Frasch mining and processing technology, developed by Herman Frasch in 1894 (*23*, p. 40), involves injecting large amounts of superheated water (163° C) down wells drilled through the sulfur deposit. Heat from the water is transferred to the formation, thus melting the sulfur, which, being heavier than water, accumulates in a pool at the bottom of each well. Compressed air is injected down each well to raise the molten sulfur to the surface. Figure 7 is a cross section through a typical Frasch sulfur production well. Once on the surface, liquid sulfur (97 to 99.8 pct S) may require only filtration, generally through a mixture of H_2SO_4 and diatomaceous earth to remove organic impurities; it is then pumped to surface storage facilities. Injected water migrates through the formation and is extracted through bleeder water wells located along the flanks of the structure away from the mining area. In some mining areas (e.g., Iraq and Poland) where the formation is not porous enough to promote sulfur and water migration, the rock is fractured by blasting the formation near the bottom of the well.

The Frasch process is used exclusively on salt diapir formations along the Gulf of Mexico off Louisiana and Texas in the United States and the State of Vera Cruz, Mexico, and on bedded evaporite formations in west Texas, the Mogul region of northern Iraq, southern Poland, and the U.S.S.R.

Elemental sulfur deposits not amenable to the Frasch process use open pit and underground methods. High- to medium-grade ore from these deposits can be roasted directly, with the resulting SO_2 gas converted to H_2SO_4. Low-grade ores are treated by a wide variety of processes, including direct melting, distillation, agglomeration, solvent extraction, and flotation to produce elemental sulfur. Sulfur ores of the Keciborlu sulfur operation near Isparta in western Turkey are mined by open pit and horizontal cut-and-fill methods. Both direct melting and flotation beneficiation processes are used to produce an elemental sulfur product.

Open pit and underground mining methods are also used on pyrite deposits. High-grade ore (45 pct S and above), after minor beneficiation consisting of crushing, grinding, screening, and washing, is roasted followed by direct conversion of the SO_2 gas to H_2SO_4. Examples of these types of operations can be found in Cyprus and along the Iberian Pyrite Belt of Portugal and Spain.

Lower grade pyrite ores are generally upgraded with flotation methods from which a pyrite concentrate can be recovered. This concentrate is then roasted, producing SO_2 that is converted to H_2SO_4. Examples of these types of operations are the operations in Sweden and Norway and those in the Kuroko type deposits of Japan.

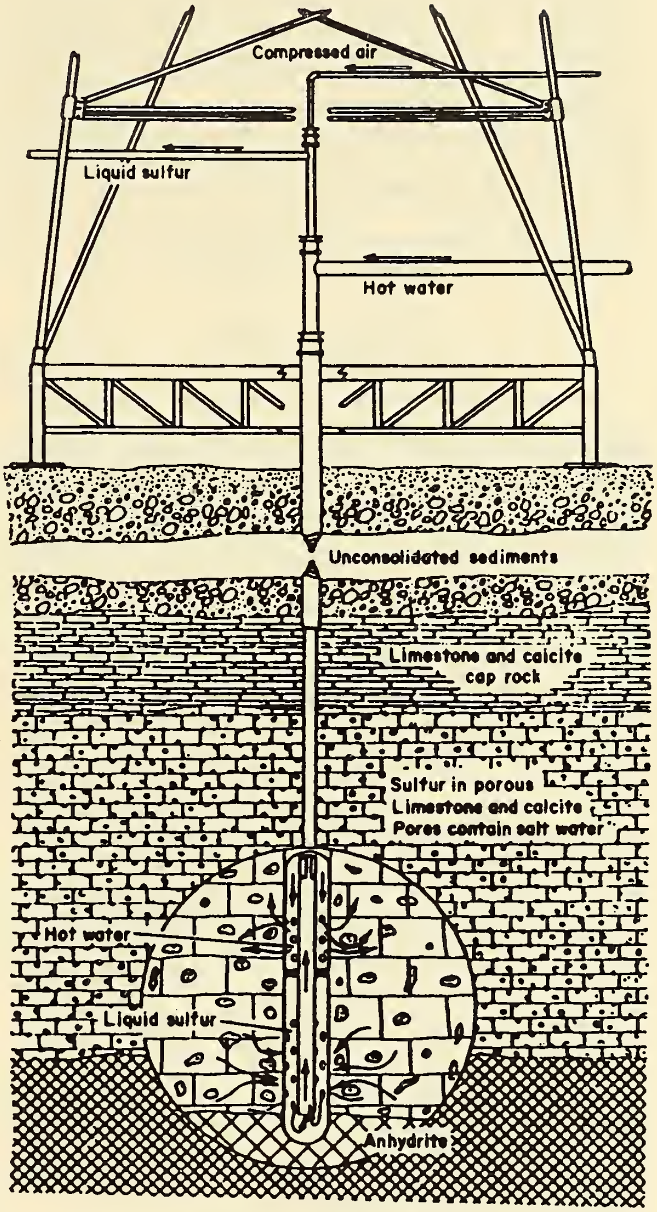

FIGURE 7.—Section through a typical Frasch sulfur production well.

CAPITAL AND OPERATING COSTS

Capital investments and operating costs were estimated for each property. These costs vary greatly depending on such factors as size of operation, mining and processing method, deposit location, and geology.

CAPITAL COSTS

Most of the 36 properties evaluated in this report have been in operation for a considerable length of time; i.e., longer than 10 yr. Therefore, some of their initial capital investment is assumed to have been depreciated. Costs presented in table 7 reflect the remaining undepreciated portion of the original capital investment and investments required for the replacement of capital to enable the operation to continue, or for construction of additional facilities or expansion of existing facilities to enable the operation to increase its production capacity. In some cases, costs reflect the investment needed to reactivate past-producing operations. These properties are not specifically identified, as confidentiality of data could be compromised.

TABLE 7.—Estimated average capital cost investments for elemental sulfur and pyrite concentrate operations
(January 1984 U.S. dollars, per metric ton sulfur)

Country	Commodity recovered[1, 2]	Remaining undepreciated capital costs[3]	Estimated capital replacement costs[4]
Cyprus	Pyr	$5.99	$8.35
Italy	Pyr	6.73	12.44
Iraq	S	W	W
Japan	Pyr	.92	5.65
Mexico	S	3.88	.88
Norway	Pyr	9.13	25.73
Portugal	Pyr	2.58	3.11
Spain	Pyr	.45	3.47
Sweden	Pyr	5.67	1.90
Turkey	Pyr, S	W	W
United States	S	.99	.44

W Withheld to avoid disclosing company proprietary data.
[1] Costs for the commodity pyrite (Pyr) are in terms of contained sulfur in the recovered pyrite concentrate.
[2] Costs for the commodity sulfur (S) are in terms of recovered elemental sulfur.
[3] Capital costs for mine and mill, development, plant and equipment, and infrastructure, remaining as of January 1, 1984.
[4] Estimated capital reinvestment for mine and mill development, plant and equipment, and infrastructure to be recovered over the life of the property.

OPERATING COSTS

Operating costs include labor, materials and supplies, energy, overhead, taxes, royalties, and insurance. Transportation costs cover the cost of storage, handling, and shipping elemental sulfur or pyrite concentrates. Shipment is generally to the nearest sulfuric acid plant, roaster or smelter, or market terminal. Operating costs do not include the conversion of elemental sulfur or pyrite concentrates to H_2SO_4.

Elemental Sulfur

Weighted-average operating costs for the 15 elemental sulfur operations are summarized in table 8. All but one property (Keciborlu, Turkey, a combined surface-underground operation) use the Frasch process to recover elemental sulfur. Four use filtration, the only beneficiation method generally required for Frasch elemental sulfur. The deposits in Iraq and Turkey, which have the lowest and highest operating costs, respectively, are included together in table 8 to avoid disclosing company proprietary data.

The 15 properties have an average operating cost of $50.82/mt of recoverable sulfur, with mining costs averaging 73 pct of total costs, transportation costs 21 pct, and milling (filtration) costs only 6 pct. After Iraq, Mexico has the lowest costs, despite high filtration costs at two of its three Frasch operations. Mexico's low overall operating costs ($49.40/mt) result from lower energy and labor costs. The Mexican Frasch operations are able to generate their own electricity from waste boiler heat and/or by recycling well bleed water, which requires less treatment and reheating, thus lowering energy costs.

In contrast, U.S. producing and nonproducing properties have costs nearly twice those in Mexico, despite far lower milling (filtration) costs – none for the five producers. Transportation costs account for 31 pct of the total for the producers but only 15 pct for the five nonproducers. The much higher U.S. costs for transportation result from the necessity to use rail transport, at about $30/mt S; however, some operations use cheaper ocean barge and pipeline transport, at just $0.77/mt S. Mexico's properties use river barge transport at about $3.50/mt S, while Iraq and Turkey use truck and rail.

Pyrite Concentrate

Weighted-average operating costs for the 21 pyrite operations are summarized in table 9. Both surface and underground mining methods are used; beneficiation methods consist of flotation or sizing. As expected, surface mining and sizing result in lower costs than underground mining and flotation.

The 21 properties have an average operating cost of $53.89/mt of contained sulfur in the pyrite concentrate. The two Portuguese and three Spanish properties have the lowest operating costs; all five use sizing beneficiation, but four of the five are underground operations. These lower

TABLE 8.—Summary of estimated operating costs, elemental sulfur operations
(U.S. dollars per metric ton recovered sulfur)

Country	Number of operations	Annual capacity range, 10^3 mt	Operating costs: Mine	Mill	Transportation	Total
Iraq and Turkey	2	W	$15.72	$3.08	$4.48	$23.28
Mexico	3	331-987	39.41	6.52	3.47	49.40
United States						
Producers	5	82-2,200	55.15	0	25.01	80.16
Temporarily closed[1]	5	85-960	84.78	1.73	15.44	101.95
Weighted average:						
U.S. properties	10	NAp	61.87	.39	22.84	85.10
All properties	15	NAp	37.12	2.81	10.89	50.82

NAp Not applicable. W Withheld to avoid disclosing company proprietary data.
[1] Includes Caillou Island mine, which closed in May 1984.

TABLE 9.—Summary of estimated operating costs, pyrite concentrate operations

(U.S. dollars per metric ton contained sulfur)

Country	Number of operations	Annual capacity range, 10^3 mt	Operating costs: Mine	Mill	Transportation	Total
Cyprus and Turkey	4	7-270	$39.35	$94.29	$9.95	$143.59
Italy	3	16-360	46.69	13.08	5.01	64.78
Japan	5	14-160	107.19	51.09	47.68	205.96
Norway	2	W	38.52	20.81	14.28	73.56
Portugal	2	W	13.58	3.01	3.99	20.58
Spain	3	50-425	12.54	2.45	3.93	18.92
Sweden	2	W	82.05	45.53	26.32	153.90
Weighted average, all properties	21	NAp	30.03	13.74	10.12	53.89
Processing method:						
Mining:[1]						
Surface	4	7-425	13.27	2.92	3.70	19.89
Underground	16	14-615	34.88	13.57	12.07	60.52
Beneficiation:						
Flotation	13	7-270	93.50	58.97	36.86	189.33
Sizing	8	43-615	16.08	3.80	4.24	24.12

NAp Not applicable. W Withheld to avoid disclosing company proprietary data.
[1] Does not include 1 operation that uses a combined surface-underground mining method.

underground mining costs result from higher mining capacities and ore feed grades. In contrast, the five Japanese and two Swedish underground operations, all of which use flotation to recover a pyrite concentrate, have the highest operating costs. Each of these mines also recovers various coproduct concentrates.

The two Norwegian operations are underground mines using flotation, and one of the three Italian underground operations also uses flotation; these three mines also recover coproduct concentrates. The other two Italian mines use sizing beneficiation.

Costs for Cyprus and Turkey (combined to avoid disclosing company proprietary information) are somewhat misleading, because they include the high cost of a combined surface and underground mining method at the Turkish operation. The three Cyprus operations are low-capacity surface mines with average operating costs roughly half that of the Turkish mine. All four use flotation beneficiation, though no coproducts are recovered.

ELEMENTAL SULFUR AND PYRITE CONCENTRATE AVAILABILITY

Using a 15-pct-DCFROR analysis, the estimated constant-dollar long-run average total cost of production for each operation in January 1984 dollars was determined for both elemental sulfur and pyrite concentrate. Their availability is presented in curves and tables as a function of the average total cost of production associated with each operation.

ELEMENTAL SULFUR AVAILABILITY

Figure 8 illustrates the potential total availability of elemental sulfur. The 15 elemental sulfur properties evaluated in this report have an estimated in situ demonstrated resource of 253 Mmt. From this resource, a potential of 185 Mmt S is available, approximately 99 pct (182 Mmt) at an average total cost of production of $131/mt (the January 1984 market price). At 1984 world production rates of Frasch and native elemental sulfur, the total resources available could supply elemental sulfur for about 13 yr. However, this life could be extended with the discovery of new deposits or if identified resources are reclassified to the demonstrated level.

Table 10 compares estimated total elemental sulfur availability by country from producers and from temporarily closed U.S. operations. Eight producers have nearly 169 Mmt S available at an average cost below $104/mt S. An additional 13 Mmt, from four temporarily closed operations, is potentially available at less than $131/mt S, and the remaining 3 Mmt, from two temporarily closed and one government owned and operated producing mine, is available at costs ranging from $156/mt to $225/mt S.

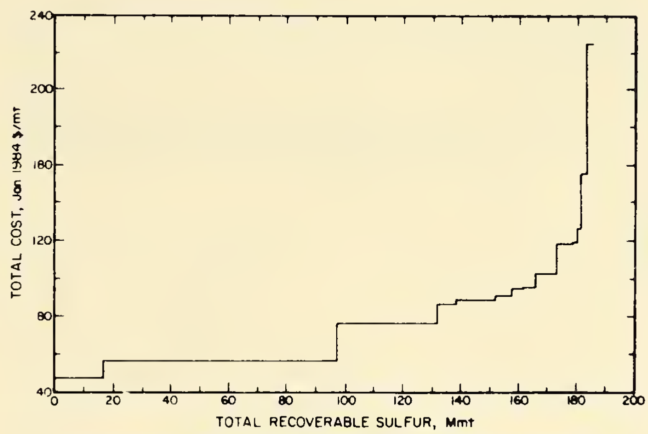

FIGURE 8.—Total availability of elemental sulfur.

TABLE 10.—Estimated total elemental sulfur availability

(Thousand metric tons)

Elemental sulfur, by source	Average total cost of production: $45.00-$90.00	$90.01-$131.00	$131.01-$225.00	Total
United States:				
Peoducers	34,844	16,486	82	51,412
Temporarily closed	0	12,850	2,214	15,064
Mexico producers	37,188	0	0	37,188
Iraq and Turkey producers	80,417	0	427	80,844
Total	152,449	29,336	2,723	184,508

Approximately 97 pct (64.2 Mmt) of the 66.5 Mmt S available from the 10 U.S. Frasch operations can be produced for less than \$131/mt S on the average; this includes 51.3 Mmt from four producers and 12.9 Mmt from four temporarily closed operations. The remaining 2.3 Mmt, available at costs exceeding \$156/mt S, is from one producing and one temporarily closed operation. Taken together, the five producers can supply 5.2 Mmt/yr S, 98 pct of which is available at less than \$131.mt; the five temporarily closed properties could supply 1.7 Mmt/yr S, 95 pct of which for less than \$131/mt.

Approximately 37.2 Mmt S is available from Mexico's three producing Frasch operations, from an estimated in situ demonstrated resource of 50.1 Mmt S, at less than \$90/mt S average operating costs. These operations could supply 2.1 Mmt/yr S for the next 14 yr, but by the early 2000's these estimated resources will have been depleted. Most of Mexico's production is exported to the United States and other world markets.

Turkish and Iraqi operations are government owned and operated. Together, an estimated 81 Mmt S is potentially available from these two properties; however, annual availability from both countries is low, owing to low production rate estimates. Most of the production is exported to European and Mediterranean sulfur markets.

Total potential annual availability of producing elemental sulfur operations is shown in figure 9. Production averaging 4.8 Mmt/yr S is possible from the 10 producers evaluated, over 99 pct for less than \$131/mt. At 1984 production, most producers will have depleted their estimated 1984 recoverable demonstrated resources by the end of the century; but three remaining producers, with less than 1.6 Mmt/yr S still available, could produce for less than the 1984 market price (\$131/mt).

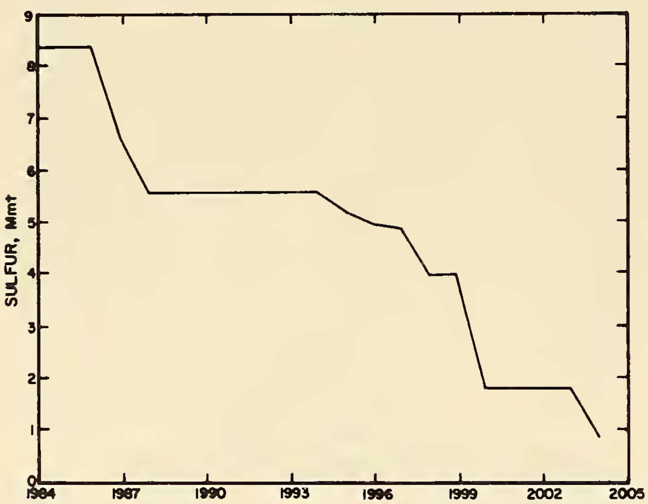

FIGURE 9.—Total annual elemental sulfur availability from producing operations (below \$225/mt S).

Because startup dates for the five temporarily closed U.S. operations are not known, their potential annual availability (fig. 10) was based on assumption that reactivation would begin in the year N. These properties together have 695,000 mt/yr S potentially available, 88 pct of which at production costs averaging less than \$131/mt. Most of these properties will have depleted their estimated 1984 recoverable demonstrated resource by the year N + 12.

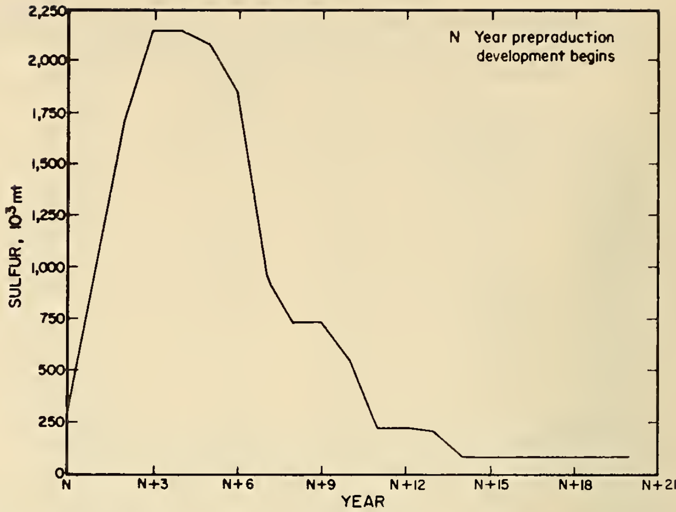

FIGURE 10.—Total annual elemental sulfur availability from temporarily closed operations (below \$225/mt S).

PYRITE CONCENTRATE AVAILABILITY

The 21 metal sulfide (pyrite) properties have in situ demonstrated resources of nearly 422 Mmt pyrite, which could supply about 279 Mmt pyrite concentrate at 46 pct S (fig. 11). Table 11 lists the estimated availability of pyrite concentrate at various average total costs of production.

Of the 279 Mmt pyrite concentrate recoverable, approximately 92 pct (257 Mmt) can be produced at average costs lower than \$43/mt pyrite concentrate (the January 1984 market price). At the 1984 rate of production, these resources could supply pyrite concentrate for 29 yr.

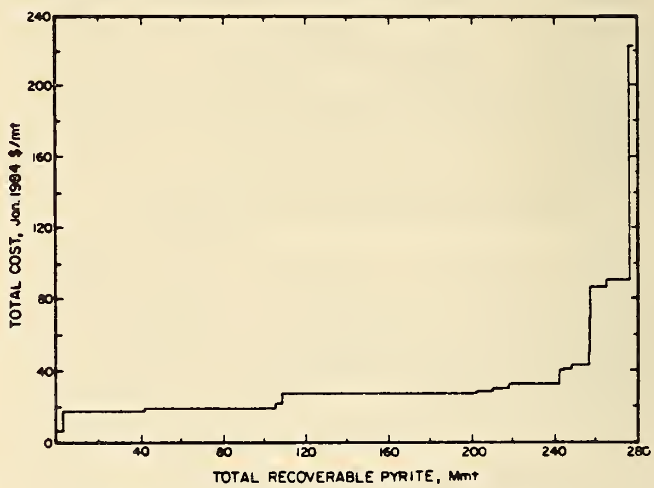

FIGURE 11.—Total availability of pyrite concentrate.

TABLE 11.—Estimated total pyrite concentrate availability
(Thousand metric tons)

Pyrite concentrate	Average total cost of production			
	0 to \$43.00	\$43.01-\$90.00	Above \$90.00	Total
Primary	232,264	868	0	233,132
Coproduct	24,132	8,127	13,469	45,728
Total	256,396	8,995	13,469	278,860

Pyrite concentrate producers that produce no other metal concentrates account for 233 Mmt of the total availability, about 99 pct of which is available for less than $43/mt. Coproduct pyrite concentrate, which is defined as any pyrite concentrate recovered for its sulfur content along with other metal concentrates, accounts for the remaining 46 Mmt. More than half of this (24 Mmt) is available for less than $43/mt, and about 845,000 mt of this is available at an average cost of production of zero, because revenues from other recovered products are able to cover the cost of pyrite concentrate production.

Table 12 compares potential pyrite concentrate availability by country over a range of production costs. Spain and Portugal, with potential availability of nearly 98 Mmt concentrate each (together, nearly 70 pct of total availability for MEC's), all at less than $30/mt, could dominate the pyrite concentrate industry well into the next century. However, at their 1984 annual production capacities, these two countries account for only 13 pct of estimated world production of pyrite concentrate.

Italy accounts for another 10 pct of MEC potential production from the evaluated properties. Of the 29 Mmt potentially available, 98 pct can by produced for less than $43/mt concentrate; the other 2.0 pct is coproduct pyrite concentrate, for which all production costs are covered by other commodities.

Japan, with 29.6 Mmt potentially available, accounts for 11 pct of total pyrite concentrate availability. About 55 pct of this (16.2 Mmt) is available for less than $30/mt; nearly 8.2 Mmt is a coproduct with other commodities. The balance of Japan's potential production, 13.5 Mmt, is coproduct pyrite available for more than $90/mt concentrate.

Figure 12 illustrates estimated potential annual availability of pyrite concentrate over various years. Average production level throughout the analyses is 5.2 Mmt/yr pyrite concentrate, peaking at 5.9 Mmt in 1990. Overall, 85 pct of this concentrate is available for less than $43/mt concentrate on the average. Primary pyrite concentrate accounts for about 3.7 Mmt/yr, with 93 pct available for less than $43/mt; coproduct production accounts for the other 1.5 Mmt/yr. with approximately 50 pct potentially available for less than $43/mt.

TABLE 12.—Comparison of total potential pyrite concentrate availability, by country
(Thousand metric tons)

Country	Average total cost of production: 0 to $43.00	$43.01-$90.00	Above $90.00	Total
Spain	98,352	0	0	98,352
Portugal	97,385	0	0	97,385
Japan	16,200	0	13,469	29,669
Italy	29,116	0	0	29,116
Norway and Sweden	15,343	0	0	15,343
Cyprus and Turkey	0	8,995	0	8,995
Total	256,396	8,995	13,469	278,860

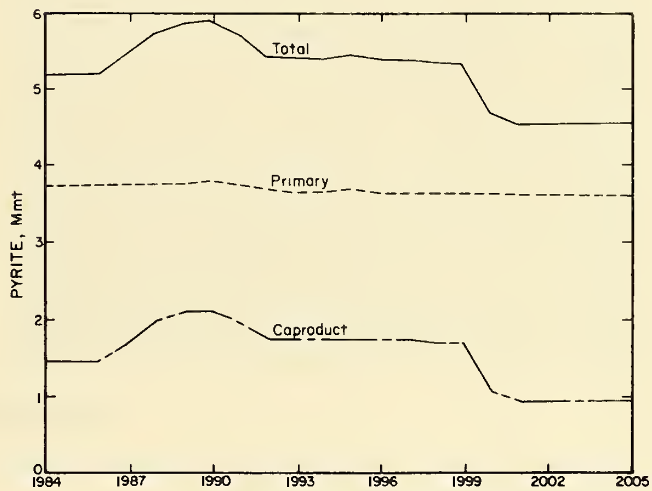

FIGURE 12.—Annual availability of total, primary, and coproduct pyrite concentrate (below $225/mt).

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CONCLUSION

Thirty-six properties (10 domestic and 26 foreign) were evaluated to determine the total potentially available tonnage of elemental sulfur and pyrite concentrate.

Availability analyses of the 36 properties indicate that 253 Mmt of elemental sulfur resources from 15 native sulfur deposits could be depleted faster than the 422 Mmt of pyrite resources from 21 sulfide deposits. Estimated total recoverable elemental sulfur is 185 Mmt. Approximately 182 Mmt S (98 pct) is available below an average total cost of production equal to the January 1984 market price ($131/mt). Eight current producers (as of January 1, 1984) account for 169 Mmt S available at about $104/mt. An additional 13 Mmt S would be available from four temporarily closed operations at an average total cost of production of less than $131/mt. Two producers, one government owned and operated, and one other temporarily closed operation account for the remaining 3 Mmt available from $156/mt to $225/mt. At 1984 rates of production these availability tonnages would be depleted within 14 yr. However, this life could be entended with the discovery of new deposits or reclassifying identified resources to the demonstrated level.

Total estimated recoverable pyrite concentrate available is 279 Mmt at 46 pct S; all 21 properties are producers. Approximately 92 pct (257 Mmt) of this pyrite concentrate is available below an average total cost of production equal to the January 1984 pyrite concentrate market price ($43/mt). Primary pyrite concentrate producers account for 233 Mmt, and coproduct pyrite concentrate producers 24 Mmt. An additional 22 Mmt (mostly as coproduct pyrite concentrate) is available at average total costs of production ranging at $52/mt to $223/mt. At 1984 production rates these availability tonnages could last about 29 yr.

The United States and Mexico should continue to dominate the North American native sulfur (Frasch) industry over the next decade. Potential average annual availability over this period is about 4.8 Mmt from producing operations. All of this sulfur is available at about $104/mt S. However, this estimated annual tonnage meets only 14 pct of the 1984 world's total elemental sulfur production level. The remainder could be made up by the production of secondary sulfur sources; i.e., recovered elemental sulfur could increase its share of the market if production from high-sulfur crude oils and sour natural gas from Mexico, the Near East, Alaska, California, Utah, and Wyoming becomes available.

Italy, Japan, Portugal, and Spain will dominate the pyrite concentrate industry into the next century, with approximately 255 Mmt of total pyrite concentrate available. Most of this tonnage is primary pyrite concentrate, available at less than $43/mt. The estimated annual pyrite concentrate tonnage from these countries account for about 47 pct of the world's 1984 estimated pyrite concentrate production.

These operations must supply pyrite concentrate at a market price that is cost competitive with H_2SO_4 production from elemental sulfur. Substantial increases in pyrite concentrate output other than to meet internal or local H_2SO_4 demand is unlikely, owing to the supply of sulfur from its many sources.

REFERENCES

1. Shelton, J. E. Sulfur. Ch. in Mineral Facts and Problems, 1980 Edition. BuMines B 671, 1981, pp. 877-898.

2. Morse, D. E. Sulfur. Ch. in BuMines Minerals Yearbook 1984, v. 1, pp. 831-849.

3. ———. Sulfur. Ch. in Mineral Facts and Problems, 1985 Edition. BuMines B 675, pp. 783-797.

4. Engineering and Mining Journal. V. 185, No. 1, Jan. 1984, p. 94.

5. Babitzke, H. R., A. F. Barsotti, J. S. Coffman, J. G. Thompson, and H. J. Bennett. The Bureau of Mines Minerals Availability System: An Update of Information Circular 8654. BuMines IC 8887, 1982, 54 pp.

6. Davidoff, R. L. Supply Analysis Model (SAM): A Minerals Availability System Methodology. BuMines IC 8820, 1980, 45 pp.

7. Clement, G. K., Jr., R. L. Miller, P. A. Seibert, L. Avery, and H. Bennett. Capital and Operating Cost Estimating System Manual for Mining and Beneficiation of Metallic and Nonmetallic Minerals Except Fossil Fuels in the United States and Canada. BuMines Spec. Publ., 1981, 149 pp.; also available as–STRAAM Engineers, Inc. Capital and Operating Cost Estimating System Handbook–Mining and Benefication of Metallic and Nonmetallic Minerals Except Fossil Fuels in the United States and Canada (contract J0255026). BuMines OFR 10-78, 1977, 382 pp.

8. Stermole, F. J. Economic Evaluation and Investment Decision Methods. Investment Evaluations Corp., Golden, CO., 2d ed., 1974, 449 pp.

9. Bodenlos, A. J. Sulfur. Ch. in United States Mineral Resources. U.S. Geol. Surv. Prof. Paper 820, 1973, pp. 605-618.

10. Hanna, M. A. Geology of the Gulf Coast Salt Domes. Ch. in Problems of Petroleum Geology. Am. Assoc. Pet. Geol., Tulsa, OK, Sidney Powers Mem. V., 1934, pp. 629-678.

11. Barker, J. M., D. E. Cochran, and R. Semrad. Economic Geology of the Misraq Native Sulfur Deposit, Northern Iraq. Econ. Geol., v. 74, 1979, pp. 484-495.

12. British Sulphur. Iraq. Ch. in World Sulphur Resources. 2d ed., 1974, pp. 155-157.

13. ———. Turkey. Ch. in World Sulphur Resources. 2d ed., 1974, pp. 52-56.

14. Strauss, G. K., J. Madel and F. F. Alosno. Exploration Practice for Strata-bound Volcanogenic Sulphide Deposits in the Spanish-Portuguese Pyrite Belt: Geology, Geophysics, and Geochemistry. Springer-Verlag, 1977, 93 pp.

15. British Sulphur. Portugal and Spain. Ch. in World Sulphur Resources. 2d ed., 1974, p. 32.

16. Bear, L. M. The Mineral Resources and Mining Industry of Cyprus. Ministry of Commerce and Industry, Geol. Surv. Dep., Republic of Cyprus, Bull. 1, 1980, 208 pp.

17. Maruyama, S., and N. Sato. Geology and Exploration of the Kurouo Deposits in Japan. Ch. 9 in Mineralogy and Metallurgy of Lead, Zinc Deposits. AIME, 1970, v. 1, pp. 171-194.

18. Sato, T. Physiochemical Environments of Kuroko Mineralization at Uchinota: Deposit of Kosaka Mine, Atita Prefecture. Ch. in Geochemistry and Crystallography of Sulphide Minerals in Hydrothermal Deposits. Soc. Min. Geol. Jpn., Spec. Issue 2, 1971, pp. 137-144.

19. Olsen, J. Genesis of the Joma Stratiform Sulfide Deposit, Central Norwegian Caledonides. Paper in Proceedings of the Fifth Quadrennial IAGOD Symposium. E. Schweizerbart'sche Verlagsbuchhandlung (Nagele U. Obermiller), Stuttgart, Fed. Rep. of Germany, 1980, pp. 745-757.

20. Wilson, M. R. The Geological Setting of the Sulitjelma Ore Bodies, Central Norwegian Caladonides. Econ. Geol., v. 68, 1973, pp. 307-316.

21. British Sulphur. Sweden. Ch. in World Sulphur Resources. 2d ed., 1974, pp. 46-52.

22. U.S. Geological Survey and U.S. Bureau of Mines. Principles of a Resource/Reserve Classification for Minerals. U.S. Geol. Surv. Circ. 831, 1980, 5 pp.

23. Haynes, W. Brimstone: The Stone That Burns. Van Nostrand, 1959, 308 pp.